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Nickel-Hydrogen Bipolar Battery Systems

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NICKEL-HYDROGEN BIPOLAR BATTERY SYSTEMS

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SUMMARY

Nickel-hydrogen cells are currently being manufactured on a semi-experimental basis. This paper will describe, at least conceptually, rechargeable nickel-hydrogen systems that more closely resemble a fuel cell system than a traditional nickel-cadmium battery pack. This has been stimulated by the currently emerging requirements related to large manned and unmanned low earth orbit applications. The resultant nickel-hydrogen battery system should have a number of features that would lead to improved reliability, reduced costs as well as superior energy density and cycle lives as compared to battery systems constructed from the current state-of-the-art nickel-hydrogen individual pressure vessel cells.

1. INTRODUCTION

The aerospace community is gradually switching from nickel-cadmium batteries to nickel-hydrogen batteries for selected applications. There is some evidence that the low earth orbit (LEO) use of nickel-hydrogen will follow the current commitments of this battery system to geosynchronous applications (GEO). The United States Air Force (Ref. 1) has been instrumental in developing this battery system in cooperation with their contractors. The hardware items that have been brought to a high degree of technology readiness are 50 Ah individual pressure vessel (IVP) passively cooled single cells (Ref. 1).

Recent studies of large manned and unmanned LEO applications in the U.S. (Space Platform, Space Operations Center, etc.) have concluded that power requirements in the range of 25 to 50 kW and higher will be required (Ref. 2). These studies also point out the desirability of higher bus voltage levels (100 > 200V DC) to reduce the weight of the power distribution network. The NASA Lewis Research Center under the NASA Office of Aeronautics and Space Technology has the responsibility: 1) to develop advanced technology components to increase the cycle lives in low earth orbit of current state-of-the-art hardware designs and 2) to investigate

cell and battery concepts that would be applicable to large multikilowatt system applications identified in future space missions of interest to the U.S.

In addressing the second area, it was evident from the initial system design studies that if contemporary nickel-hydrogen design concepts were used, several undesirable system features would result. First, high voltage could only be obtained through either the series connection of 100 to 200 individual single cells or the use of high capacity DC to DC conversion equipment. This equipment currently weighs about 5 kg/kW, although future developments might reduce this to 1.0 kg/kW. For the former, the reliability and weight impact associated with the interconnection of so large a number of cells is undesirable. The required thermal control subsystem for this number of individual cells that depends entirely upon passive cooling would at best result in a system with a lower volumetric energy density. This would compound the problem of the already low volumetric energy density of nickel-hydrogen single cell devices. For the latter, the weight, cost and inefficiency of DC to DC conversion is not a good design choice.

As a result of some initial thoughts given to this problem, the idea of a bipolar nickel-hydrogen battery system appeared to circumvent some of the problems associated with contemporary nickel-hydrogen battery system designs. This idea is depicted schematically in Figure 1. Although this is very preliminary, the exploded view is meant to imply the use of a bipolar stack of cells held together with end plates and tie bolts. In this version, a heat exchanger is located within the pressure vessel itself. The hydrogen gas is circulated through the cells and over the fins of the exchanger. The construction is a marriage of fuel cell and battery technology. It is very similar to an alkaline hydrogen-oxygen fuel cell using trapped electrolyte in each cell. The major difference, of course, is that the gaseous oxygen electrode would be replaced by a nickel electrode. Fuel cells of the type used in the Shuttle Orbiter which represent the current state-of-the-art are made up of cell stacks assembled in a bipolar manner. In like manner, stacks of nickel-hydrogen cells would have cooling plates located

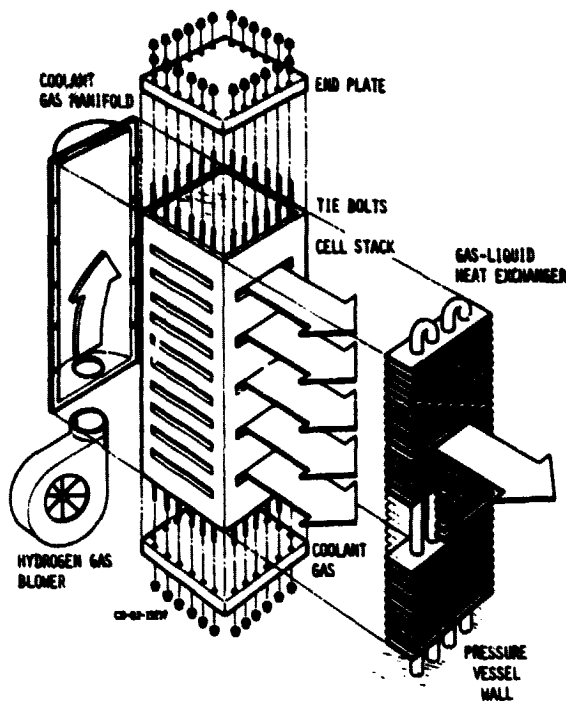


Figure 1 Exploded view of a nickel-hydrogen battery system featuring active cooling and bipolar cell construction.

appropriately for heat removal purposes. The cell stack would be placed inside a pressure vessel much like other nickel-hydrogen devices. The use of an active heat removal subsystem is expected to improve the volumetric energy density considerably when compared to a system made up of the traditional 50 Ah IPV or proposed 6 volt 50 Ah common pressure vessel (CPV) designs.

2. NICKEL-HYDROGEN ELECTROCHEMISTRY

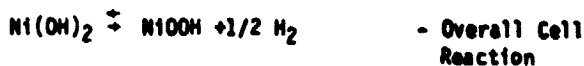
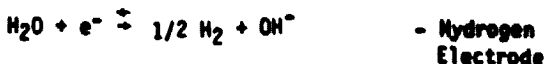
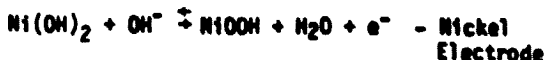
Rechargeable nickel-hydrogen cells are relatively new. Russian work by Tsenter and Kloss (Ref. 3) appears to have been the pioneering effort. This was followed later by the German work of Plust (Ref. 4) and the American work of Swette (Ref. 5). These were followed by a number of other efforts in the U.S. and Europe, and later in Japan (Ref. 6). A recent review on the topic of nickel-hydrogen technology has been prepared by Batelle, Columbus Laboratories (Ref. 7). The span of interest in this electrochemical system covers aerospace as well as terrestrial applications and stems from a combination of desirable features. The primary ones are the high degree of reversibility of the individual electrodes, the constant electrolyte concentration over a complete charge/discharge cycle and the ability of the cell to undergo a certain degree of overcharge and overdischarge. Some investigators feel that the cell pressure will be a useable measure of the state of charge. The potential for reduced weight when compared to nickel-cadmium cells is also an important advantage.

Working with all these advantages, developers have been busily engaged over the past decade to produce experimental devices that would possess all the above listed advantages and benefits.

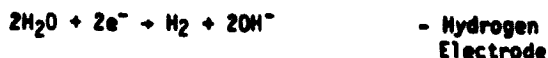
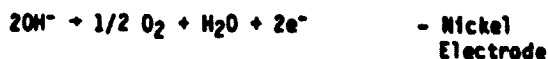
The nickel electrode has been rather thoroughly characterized in terms of its oxygen evolution characteristics during charge and the relative merits of a variety of methods by which active material is placed within the porous nickel sinters; the most popular form of substrate for the reactive material. In like manner, the morphological phenomenon associated with the different crystal lattice dimensions of the reactive material has been studied in detail by a British group (Ref. 8) and an American group (Ref. 9), to mention just a few, to gain insight into the effect of the gradual structural changes on the oxygen evolution characteristics and plaque integrity, respectively. Although the nickel-hydrogen system is rather new, nickel electrode studies have been underway ever since the introduction of the Edison cell during the last century. The fuel cell studies that have been carried out in many parts of the world have contributed to the sophisticated understanding of the hydrogen electrode. For completeness, the half-cell reactions involved in cells purposely made to be limited in the amount of nickel oxide are listed below.

Chemistry and Electrochemistry of Nickel-Hydrogen Cells

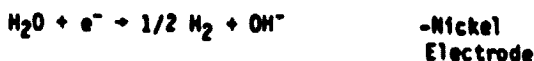
Charge-Discharge



Overcharge



Reversal (Nickel Limited)



Although many of the cycling test results for Ni-H₂ have not reached the open literature, it can be stated that encouraging results have now been achieved for geosynchronous orbit (GEO) test regimes. For low earth orbit (LEO) test regimes cycle lives have been observed that are far below those usually associated with nickel-cadmium cells.

Although the exact reasons for failure in Ni-H₂ cells may be a matter of conjecture and may vary from manufacturer to manufacturer or from cell configuration to cell configuration, it will be suggested here that the problems stem from physical chemical problems rather than electrochemical problems.

3. NICKEL-HYDROGEN PHYSICAL CHEMISTRY

A wide variety of physical chemical phenomenon that have been included in classical texts (i.e. Ref. 10) do influence cell behavior. Unfortunately they are not often fully appreciated by those involved in the design and construction of electrochemical devices. These phenomena include 1) isopiestic considerations for the redistribution of water among cell components, 2) diffusion, migration and convection for the redistribution of the ionic components within the electrolyte, and 3) capillary pressure, pore size distribution and other factors related to the redistribution of electrolyte between the combination of cell components. To these three types of redistributions the chemical recombination of the hydrogen and co-evolved oxygen from the nickel electrode and the subsequent dispersal of the product water must be considered. Likewise, provisions must be made for the oxygen and hydrogen which is generated during the recharge portion of the cycle so that the gases can be evolved without an excessive entrainment of electrolyte (spatter) along with the disengaging gas bubbles.

A recent paper covering the general topic of pore size engineering in cells that contain an amount of electrolyte that is less than that required to fully saturate all of the cell components (Ref. 11) addresses some of these issues. It is not the intent of this short paper to fully address all the physical chemical considerations that are important to nickel-hydrogen cells. It is suggested, however, that the failure to adequately make provision for these phenomena have resulted in cycle lives and performance levels that are far below those which can be expected from an electrochemical point of view.

4. SHORTCOMINGS OF CONTEMPORARY NICKEL-HYDROGEN DESIGNS

A careful review of the current nickel-hydrogen technology will reveal several kinds of problems that still remain. The main problem appears to be a lack of long cycle life at deep depths of discharge. This is usually attributed to a loss of structural integrity of the nickel electrode under the high mechanical stresses created by the cycling reactive material (Ref. 9). Closely related to that problem is the apparent dry-out of the cell or loss of electrolyte. This could be caused by a gradual change in the pore size and/or the pore size distribution characteristics of the nickel electrode during cycling or

the physical loss of electrolyte from the cell stack. Wicking techniques have helped in the latter problem area. These types of difficulties are those that would be expected to gradually disappear as this technology matures.

A different type of problem, yet one that is possibly the most important, is related to the volumetric energy density of a completed large battery system. Reference 12 contains a photograph of a completed system of the type that would be useful for a small space application. What is noted is the very low packing density of the individual pressure vessels. This is in part caused by their shape (cylinders with hemispherical end caps) and in part by reliance on the transfer of heat from the cell stack to the cold plate by passive heat transfer processes.

The dependence upon passive cooling techniques limits the resultant battery in several ways. First of all the discharge rate is constrained by the requirements to limit the temperature gradient from the center of the cell to the outer portion where the heat is transferred across the cell wall to the cold plate. Excessive discharge rates would result in excessive "drying" conditions at the center of the cell as a consequence of the redistribution of water in the vapor phase as the system attempts to maintain isopiestic conditions throughout the cell. This also impacts the relative ease by which cell sizes can be scaled up or down from a baseline configuration. It is essential to give careful consideration to the new temperature profiles resulting from a new configuration.

A further shortcoming is related to the oxygen management techniques currently used in nickel-hydrogen cells. The oxygen evolved during the latter portions of the recharge segment of the cycle must be recombined with the stoichiometric amount of hydrogen. At the normal operating conditions of these cells the nickel electrode does not represent a suitable catalytic surface for the chemical recombination of these gases. The hydrogen electrode represents an excellent surface for this recombination. The chemical reaction of forming water from hydrogen and oxygen is of course very exothermic and therefore care must be exercised to limit the rate at which these two reactants come together. This can be done by limiting the rate of overcharge to an acceptable value and then trust that the oxygen and hydrogen react uniformly over the entire surface of the electrode. Unfortunately this has not always been found to be the case. If a separator is used where the pore size distribution permits a certain degree of gas permeability, what has been speculated to be oxygen bubble buildup takes place and "popping" results as these accumulations of oxygen abruptly recombine. This can result in sintering of the catalyst surface and/or local melting of the teflon/catalyst agglomerates that make up the hydrogen electrode. If separators are used which possess a very high bubble pressure, the oxygen must travel along the face of the nickel electrode out into the bulk hydrogen space and back into the back side of the hydrogen electrode. In this case the recombination would be expected to take place around the outer perimeter of the electrode. Here also the concentration of the chemical reaction could

result in undue damage to the electrocatalyst surface of the electrode.

Finally the use of contemporary cell designs to construct large storage systems involving possibly hundreds of individual cells would need to be assembled in series or series parallel strings. The many connector straps become a source of energy loss and reliability may be compromised.

The battery system design to be considered here circumvents many of the inherent problems still associated with nickel-hydrogen cell and battery technology. These ideas are in part restricted to larger systems (possibly greater than 10 kW) where the parasitic energy losses associated with an active cooling subsystem would not represent an undue penalty to the overall system. In reality, they represent a simple adaptation of principles that have been well established in the aerospace fuel cell technology to nickel-hydrogen cell and battery system design.

5. BIPOLAR BATTERY DESIGNS

Figure 1 depicts one of several preliminary designs for a large nickel-hydrogen battery system. It is shown in an exploded view to illustrate the main features that are common to all the designs but need not have the exact configuration depicted here. The major features include individual cells that are large flat sheets connected together in a bipolar manner. Using this technique, a cell stack of any voltage level could be produced by a simple stacking together of the required number of individual cells. The capacity of the cells is a simple function of the cell area. Overall battery capacity and redundancy considerations are met by grouping the required number of cell stacks. Each cell stack as shown in the figure would be housed within its own pressure vessel. In the configuration illustrated here, hydrogen is used as the cooling fluid picking up heat as it flows through passages between individual cells. The gas is cooled via a heat exchanger in the spacecraft fluid cooling loop. A blower forces the hydrogen up the plenum or manifold on the backside of the stack and across the individual cooling plates. The hydrogen that is consumed electrochemically has access to each cell in a manner that will be discussed in more detail below.

The end plates and tie bolts are used to insure the correct compression and alignment of all the cell parts.

A more complete discussion of two variations of this design was the topic of a recent paper in the 1982 IECEC Proceedings (Ref. 13). These variations resulted from a preliminary design effort carried out in-house at the Lewis Research Center by two design teams. The reader is referred to that paper for a more in-depth discussion of the design considerations as they related to a 35 kilowatt battery for LEO applications. The unique findings of this preliminary design are related to the energy density (both gravimetric and volumetric) of these battery systems in comparison to ones based on the contemporary 50 Ahr IPV cells. Table I summarizes this information. For the bipolar battery an average of the two design concepts is given.

Table I

Energy Density Projections Based on
Two Cell Types

Battery Type	Gravimetric Energy Density ^b		Volumetric Energy Density ^b	
	Whr/kg	Whr/lb	Whr/l	Whr/ft ³
Bipolar ^a	8.6-9.5	19-21	28-35	800-1000
IPV ^c	5.5-6.8	12-15	1.2-1.4	30-40

- a - Pressure Vessel - cylinder with torispherical heads
- b - 100 percent depth of discharge, 1.2 average cell discharge voltage
- c - Battery based on US Air Force/Hughes individual pressure design.
- d - Estimated, IPV single cell, 950 Whr/ft³

Not shown in Figure 1 are the provisions made for an improved oxygen management technique as pointed out above. Use of the hydrogen electrode catalyst surface to chemically recombine the oxygen can result in loss of catalyst area and possible melting of the teflon/catalyst agglomerate and thus performance loss. These designs incorporate a separate catalyst surface located behind the nickel electrode. Further details on this topic can be found in Ref. 13. The major advantage of the proposed bipolar designs appears to be the large improvement in the volumetric energy densities in comparison to those achievable with contemporary IPV cell hardware.

To obtain an early conformation of the bipolar concept a multicell stack of cells is currently under construction. This will use available hardware articles that were used in a water electrolysis stack coupled with nickel electrodes available from a past battery development program. The cell size (area) is about 220 cm² (.24 ft²) and the capacity of each nickel electrode about 8 Ah. Ten cells will be connected in series and the resultant stack placed within a fully instrumented pressure vessel. This battery is currently in the final stages of assembly and testing is scheduled to begin in August 1982. Active cooling has not been incorporated in this feasibility test. This will be followed by an effort to develop the full size cell and stack hardware.

Hughes Aerospace Co. is currently under contract to the Lewis Research Center of the NASA to do a more formal design study of this general concept and compare it with designs based on contemporary IPV cells as well as with the more recent US Air Force design studies with common pressure vessel cells (Ref. 14). The common pressure vessel studies are currently addressing a design in which six stacks of IPV electrodes are placed electrically in series within a common container.

These bipolar designs represent a radical departure from contemporary nickel-hydrogen cell and battery practice designs yet when viewed from the framework of fuel cell system technology

that is already in place, these designs are a natural and logical extensions of established principles and practices. The following section will briefly review some of these principles as they relate to bipolar nickel-hydrogen battery designs.

6. APPLICABLE TECHNOLOGY FROM THE FIELD OF ALKALINE FUEL CELLS USING TRAPPED ELECTROLYTES

Although nickel hydrogen cells employ one electrode that has been a standard for many years in several alkaline electrolyte cells and another electrode that has been the better understood of the two used in hydrogen-oxygen fuel cells, the resultant marriage in the form of nickel-hydrogen cells very closely resembles a traditional electrolyte-starved alkaline cell. The capacities are nominally the same as for the nickel-cadmium cells they are trying to displace. They contain groupings of anodes and cathodes connected in parallel and are manufactured as single cells to be connected together, cooled, instrumented, and controlled by the user. Alkaline fuel cells with trapped electrolyte are currently typified by the power plants used on the Space Shuttle. By contrast, in these devices individual cells are grouped together in "stacks" where the cells are connected together in a bipolar manner. These power plants incorporate cooling/heating plates between each cell, and all the required logic and controls for proper startup, operation, and shutdown. That is, fuel cells are delivered by a manufacturer (in this case United Technologies Corporation) as a complete power system whereas a "battery" manufacturer usually delivers a certain number of single cells. In turn then, a second organization tests these single cells for acceptance and then adds the required interconnections, instrumentation, controls, etc.

Aside from the different approaches to the system objective for both technologies, the fuel cell technology has had to overcome certain obstacles that has resulted in a wealth of specialized insites that are largely transferable to the task of designing large bipolar nickel-hydrogen batteries.

6.1 Bipolar Connections

Utilizing bipolar cells that employ "through" conduction rather than relying on external interconnections eliminates several problems. In groupings of electrodes connected in parallel where the electrolyte is shared or communicates, (as in IPV cells) there can be a problem of current balance among all of the components. The problem of tab breakage and corrosion is also present. Probably the most difficult problem associated with electrodes with tab connectors is the requirement for a reasonable lateral conductivity in order to preclude gross maldistributions of electrochemical activity across the face of the electrode. When bipolar electrodes are used, only current flow perpendicular to the electrode plane need be considered. In this case less conductive, lighter weight electrode substrates can be considered.

6.2 Optimum Electrolyte Volume Considerations

In fuel cells where two gas electrodes are used,

the concept of optimum electrolyte volume becomes very important. This general type of behavior can also be expected for nickel-hydrogen cells and has been studied in detail by Gutmann (Ref. 15). Very briefly, the optimum electrolyte volume of a fuel cell, nickel-hydrogen cell or nickel-cadmium cell is that volume of electrolyte which yields the maximum performance of the cell (Ref. 17). For the case of gas electrodes it arises from a compromise between not having enough electrolyte creating a deficiency of three-phase reaction sites (electrolyte film, reactive gas, and catalyst particles) and too much electrolyte which causes flooding of the reaction sites. Traditional Ni/H_2 cells perform poorly when there is a deficiency of electrolyte but do not typically exhibit poor performance when excess electrolyte is present. Due to the requirement for recombination of oxygen, the usual practice is to operate in the electrolyte-starved condition. In this case the oxygen has access to the negative electrode across the partially saturated separator between the two electrodes. (Ref. 15).

6.3 Volume Tolerance

The term volume tolerance is used to refer to the performance characteristics of a cell as it operates under conditions where the electrolyte volume is in excess of the optimum amount and less than the optimum amount. Figure 2 depicts the electrolyte volume tolerance characteristics of three types of fuel cells. To be noted is the point that constructional variations have been introduced as the technology has matured which has resulted in an increase in the volume tolerance characteristics of, in this case, an alkaline hydrogen-oxygen fuel cell. Reference 11 serves to illustrate the need for cell constructional features that result in the widening of their volume tolerance characteristics. In nickel-hydrogen designs added volume tolerance can be incorporated into the separator (Ref. 11) or into the nickel electrode (Ref. 16) or into a reservoir plate as is the standard practice in alkaline fuel cells (Ref. 17).

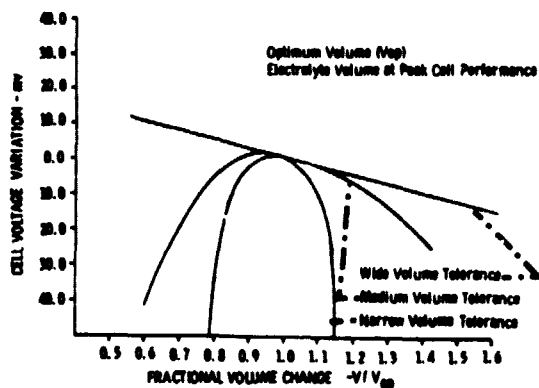


Figure 2 Cell performance as a function of electrolyte volume for fuel cell configurations with different volume tolerance characteristics.

6.4 Active Cooling Techniques

Fuel cell systems of all types employ active cooling in one form or another. Typically a cooling plate is placed between every fuel cell or every third or some other regular interval along the stack. The circulation of a gas or liquid coolant then establishes a rather definite temperature profile across the face of the cell. This temperature profile is very important when the effect of driving forces related to the maintenance of isopiestic conditions throughout the stack of cell components is considered and accounted for through proper component design. A second important feature of having active cooling techniques within a cell or stack is related to the ease and confidence by which that item can be scaled to larger or smaller sizes. One of the major impediments to scaling up traditional cells is related to the complications that arise from the new thermal environment associated with the larger cells. Since cells with starved electrolytes use thermal conduction as the primary mode of heat transfer and natural convection or further thermal conduction takes place at the outside of the cell, large cells are often subject to severe overheating problems. For these reasons scaling traditional cells to larger sizes has not been very successful.

6.5 Gas Permeable Hydrophobic Films

Different manufacturers of gas electrodes have explored the use of non-wetting porous films as an aid in preventing the loss of electrolyte from the gas side of hydrogen electrodes. The current US Air Force hydrogen electrode uses such a film. In past contractual efforts with both the NASA and the US Air Force, the use of these films has been successfully demonstrated in devices wherein water vapor was being continuously evaporated from a KOH solution. These vapors along with any accompanying droplets of bulk electrolyte were separated one from another using one of these barriers. Ref. 15 contains a fuller description of these evaporative devices. The utility of one of these droplet barriers could be of use in nickel-hydrogen cells in an overall scheme of electrolyte management. Current nickel-hydrogen designs use "wall wicks" to help return spattered electrolyte droplets to the cell separators. In high voltage stacks shunt current paths must be eliminated completely. This, coupled with the requirement to contain the electrolyte within the individual cells, would suggest that the hydrogen gas entering and leaving each cell should pass through one of these film devices.

7. CONCLUDING REMARKS

Nickel-hydrogen cells are currently emerging as the successor to nickel-cadmium cells for aerospace applications. Based on state-of-the-art alkaline fuel cell technology, several significant improvements can be made to state-of-the-art nickel-hydrogen cells. These are related to a better appreciation of electrolyte volume management and volume tolerance considerations within the cells. However the major opportunities for fully capitalizing on the attractive features of the nickel-hydrogen electrochemistry rest with large multikilowatt energy storage

systems. Here, the use of active cooling and bipolar cell construction results in significant advantages over the current IPV technology. These advantages include an almost doubling of the gravimetric energy density and even larger increases in the volumetric energy density. The resultant high voltage stack located within a common pressure vessel makes an ideal building block for large advanced energy storage systems for applications like the proposed manned space station. Built as a complete system with all the required monitoring and system control will minimize the number of connections and wires to the main spacecraft. Two teams have already carried out a preliminary design and their summarized results have been reported (Ref. 13). A small preprototype system is currently under construction at the Lewis Research Center of the NASA and a design study for 35 kW system is being carried out with the expectation that a hardware technology effort development will be underway in 1983.

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